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EXPERIMENTAL RESULTS FOR INDUCTIVE AND CAPACITIVE HEATING OF A HYDROGEN PLASMA BY A R.F. COIL

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ABSTRACT

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Experimental results for heating a plasma by a r.f. coil in the presence of an axial magnetic field are analyzed using an electric circuit model based on the geometric character of the apparatus. This model indicates that the presence of plasma adds a "lossy" capacitor in parallel with the r.f. coil. Consequently power goes into the plasma both inductively (E_θ) and electrostatically (E_r, E_z). It is believed that the latter mode of power transfer is responsible for anomalies noted. The amount of power in each mode was calculated and shown to vary with magnetic field. The inductive power transfer increased at magnetic-field values near the atomic and molecular ion cyclotron fields, whereas the electrostatic power decreased or increased depending upon which parameter -- power or coil voltage -- was held constant. Maximum total power transfer also occurred near the atomic and molecular ion cyclotron fields. The electron-density decrease noted near the resonant points appeared to be related to the induction mode only. Some deficiencies of this over-simplified model are noted.

AUTHOR

INTRODUCTION

One of the problems which exists in the plasma physics field is that of setting up in the laboratory experimental conditions which are identical to those assumed in theoretical work. For example, considerable theoretical work has been done in the field of r.f. coil-generated plasma waves, yet many discrepancies are noted when these waves are investigated experimentally. Such discrepancies as wave lengths different from calculated values, shifts in resonant frequency toward low magnetic fields rather than toward high magnetic fields, amplitudes of the component parts of the wave different from calculated values, and non-appearance of resonances when such should be obtained have been noted. These are undoubtedly due to deficiencies in the experimental setup.

As part of our overall r.f. plasma heating program we have been attempting to study at least one experimental factor which may be partially responsible for the difficulties. This factor is the r.f. coil itself. Such coil not only generates azimuthal electric fields, but also radial and axial fields under the coil and even, under certain conditions, causes axial electric fields to exist in the plasma not directly under the coil. Hence, the coil is not quite the simple source of r.f. power that one would prefer.

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Extensive experimental data have been obtained in our r.f. apparatus. An analysis of these data using an equivalent electric circuit for the coil will help determine how much power is being transferred to the plasma by the induction (azimuthal heating) mode and by the electrostatic (radial and axial heating) mode. This investigation is not complete; however, the results obtained to date are quite informative and are being presented for this reason. All of the data have been obtained using hydrogen gas at 2 microns pressure.

EXPERIMENTAL CONFIGURATION

The first slide (I) shows the experimental configuration being used. Only the left half of the apparatus is shown; the right half is identical except for elimination of the ion source. The apparatus is located in a mirror-type magnetic field. A Philips Ionization Gauge (P.I.G.) discharge is used as the ion source which generates a plasma column as shown. The plasma column diameter is smaller at the mirror. A four-section, four-turn-per-section coil of the Stix-type is connected to an r.f. source operated at 6.5 megacycles. Underneath the coil and inside of the glass tube is an aluminum shield which is slotted axially and which is electrically isolated from ground. Lack of time prevents discussing the reasons for this shield, but I will say that only minor operating differences are noted when it is removed.

At the bottom of the figure the coil has been represented as an inductance L in series with the a.c. resistance R_c of the coil. When plasma is present there is an additional resistance R_p which represents the additional induction heating load due to the plasma, the greater the load the larger the value of R_p. The shield is located such that there can be capacitive coupling between the high voltage of the coil and the shield. This coupling is represented by C. Since the coupling results in a voltage on the shield, there is a radial electric field between the shield and the plasma column and an axial electric field between the shield and ground so that currents can flow from the coil to the shield and to ground through the plasma. The resistance path of this current has been designated R_1. There is also an additional capacitance C_1 due to the combined capacitances of the shield to ground and the shield to the plasma. The net result of this branch consisting of C, R_1, and C_1 is the existence of a "lossy" capacitor in parallel with the coil.

For the present analysis the capacitance C_1 has been assumed to be zero, although work is currently underway to include C_1 in the analysis. Therefore, the circuit to be discussed is the four-element circuit consisting of C, R_1, L, and R where R_p and R_c have been lumped into R.

CIRCUIT ANALYSIS

This circuit is analyzed using the experimentally determined parameters of r.f. power P, peak coil voltage E, current I, peak shield voltage E_s, inductance L, and coil resistance R_c. Using these measured parameters C, R_1, and R can be calculated. The capacitance C should be constant (over a reasonable range of conditions) and this constancy can be used to strengthen one's belief in the analysis. Once C, R_1, and R are determined the power in R_1, R_p, and R_c can be calculated.

The method of analysis is summarized in the next slide (II). The actual circuit has an equivalent circuit which consists of an inductance $\mathcal{L}$ and resistance $\mathcal{R}_e$ related to the four circuit elements by the equations at the bottom. Three equations in three unknowns are shown. These simply show that the power in the actual circuit is the sum of the powers in R_1 and R, that the inductive reactance in the equivalent circuit is $\frac{E}{\sqrt{2}I}$, and that the power in the equivalent circuit is $I^2\mathcal{R}_e$. The basic assumptions are that L is constant, $(WL)^2 \gg R^2$ and $(W\mathcal{L})^2 \gg \mathcal{R}_e^2$. The factors $\sqrt{2}$ and 2 enter in converting peak voltage to rms voltage. The equations resulting from substitutions are fourth order and were solved on the IBM 7090 computing machine.

EXPERIMENTAL RESULTS AND DISCUSSION

A typical set of data which has been analyzed by this method is shown in the next slide (III). Generally, data have been obtained for two operating conditions: (1) power output of the r.f. source held constant, and (2) coil-voltage held constant. This latter condition implies that coil current, and hence the induced azimuthal vacuum electric field under the coil, is constant. The curves indicate that power absorption is greater in regions of fields slightly less than the atomic and molecular hydrogen-ion resonant-field values indicated. Other data obtained with larger r.f. power indicate a shift to even lower fields.

Values for the capacitance C were calculated using the equations. The average value of C was about 27 micromicrofarads and constant within the experimental error. At higher power there is a definite trend away from this value. At the present time we are unable to show that such trend is detrimental to the analysis.

Typical values for R and R_1 are shown in the next slide (IV). These curves also show two definite peaks which must be related to the atomic and molecular resonances. Originally it was hoped that the peaks and/or valleys for R and R_1 would occur at different magnetic fields and that the peak for R would occur exactly at the atomic and molecular resonant fields or at slightly greater fields than this if ion cyclotron waves were being generated. Such facts would indicate the presence of at least two separate and distinct phenomena, one of which would be the resonance associated with azimuthal heating of ions or generation of ion cyclotron waves. It is not apparent that such trends are present at the low fields. At high fields there is a definite shift of the peaks and R does peak close to the molecular resonant-field point. This is encouraging and it is hoped that more detailed analysis will show the expected trends more strongly.

The distribution of r.f. power among R_p, R_c, and R_1 are shown in the next two slides (V and VI) and differences are noted depending on whether constant-power data or constant-voltage data are considered. This slide (V) shows constant-power data. The induction mode (power in R_p) shows peak power transfer near the two resonant points, whereas the electrostatic mode shows more or less a mirror image by decreasing at these points. The power loss in

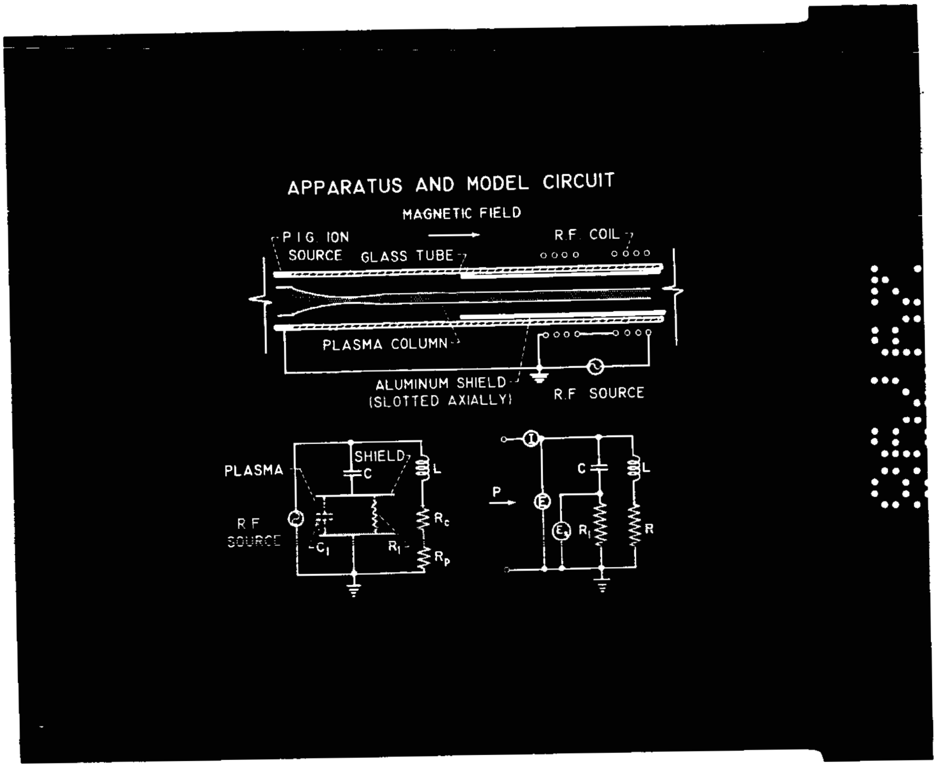
R_e is relatively constant and amounts to about 11 percent of the total power. The power in the two modes is divided into about equal amounts except at the peaks where more power goes into the induction mode.

Power divides somewhat differently for the constant-voltage data as shown in the next slide (VI). In this case both the induction and electrostatic modes exhibit peaks, but there is a marked shift toward lower fields for the electrostatic mode. Also, more power goes into the plasma by this mode at the lower fields than goes in by the induction mode. The power in the induction mode is still greater at the larger fields.

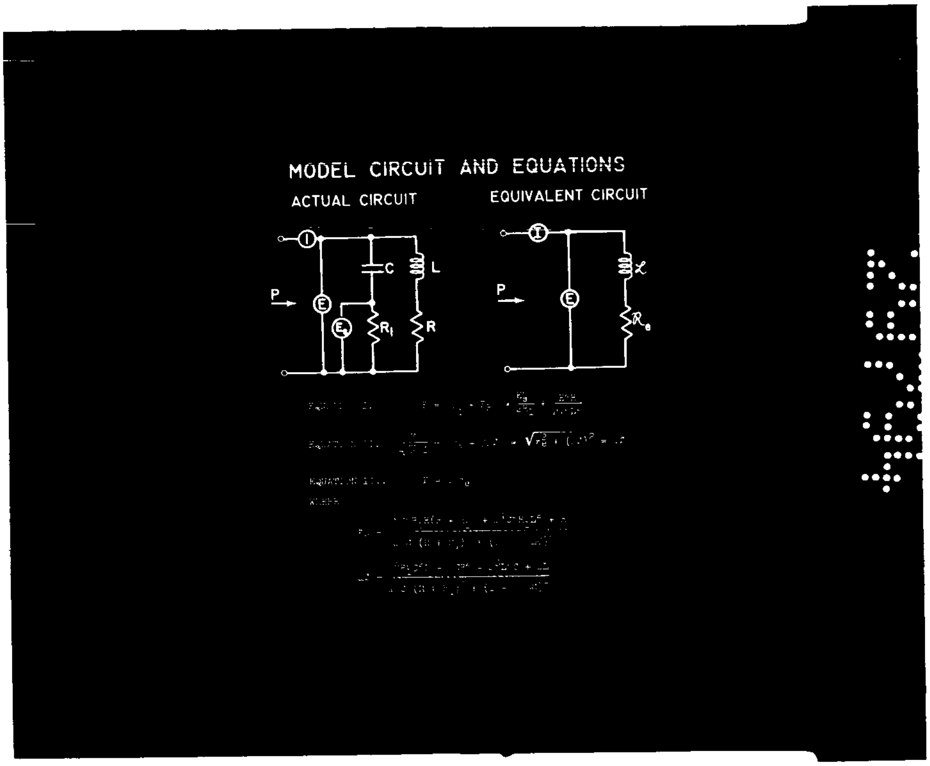
The only internal plasma measurement available to us which might be correlated with these data is the microwave interferometer measurement of electron density as shown on the last slide (VII). This curve is typical of either the constant-power or constant-voltage data. The electron-density level is of the order of 10^{11} electrons per cubic centimeter. It can be seen that there is a general increase in density as the magnetic field is increased, but there is a decrease in density just below the atomic and molecular resonant points. These decreases correlate only with the induction mode since it will be remembered that the trends in the electrostatic mode were different for the constant-power and constant-voltage runs. Hence, it can only be concluded that when power is absorbed by ions from the azimuthal field less power is available for the ionization process since ions are not an efficient way to ionize a gas.

SUMMARY AND CONCLUDING REMARKS

An over-simplified electrical model of an induction coil heating a plasma in a magnetic field has been developed from the geometric character of the apparatus. The model shows that the plasma adds a "lossy" capacitor in parallel with the coil. Considerable power is absorbed by this capacitor and may be responsible for the observed shifts in resonances away from the theoretical resonant values. The powers in the induction and electrostatic modes have been determined and are shown to vary with magnetic field. A decrease in electron density near the resonant points appears to be related to the induction mode only. It is believed that the type of analysis described herein offers a means of more logically describing the conditions which exist under the coil and can possibly clarify some anomalies noted in plasma experiments.

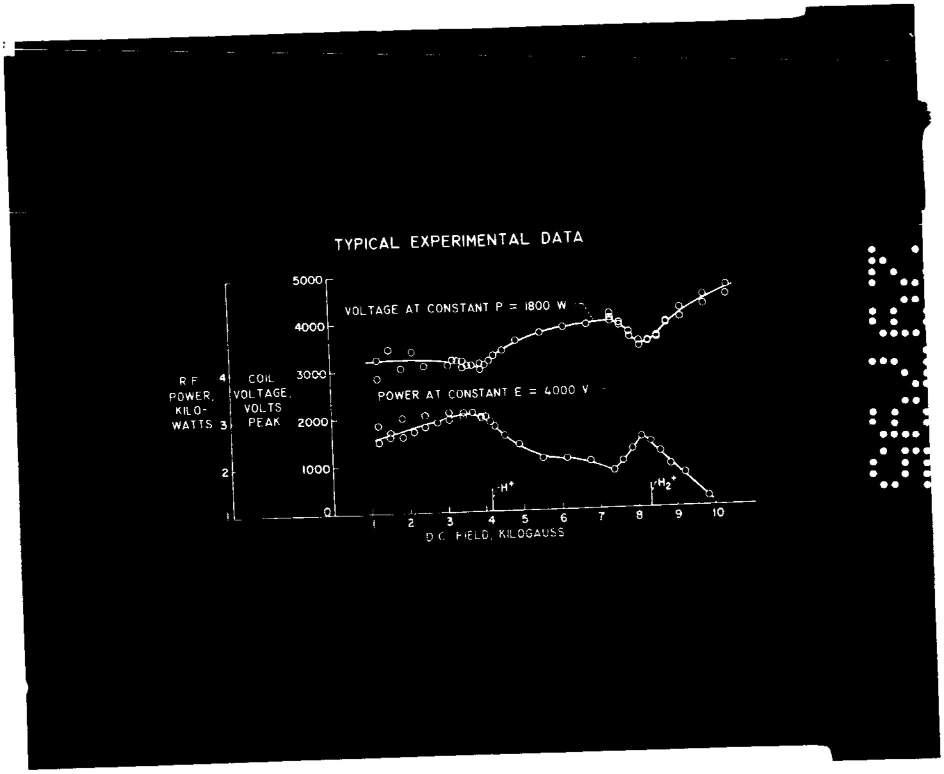

APPARATUS AND MODEL CIRCUIT
MAGNETIC FIELD
P.I.G. ION SOURCE
GLASS TUBE
R.F. COIL
PLASMA COLUMN
ALUMINUM SHIELD (SLOTTED AXIALLY)
R.F. SOURCE
PLASMA
SHIELD
C
L
R.F SOURCE
C_1
R_1
R_c
R_p
P
I
E
E_1
R_1
C
L
R

I

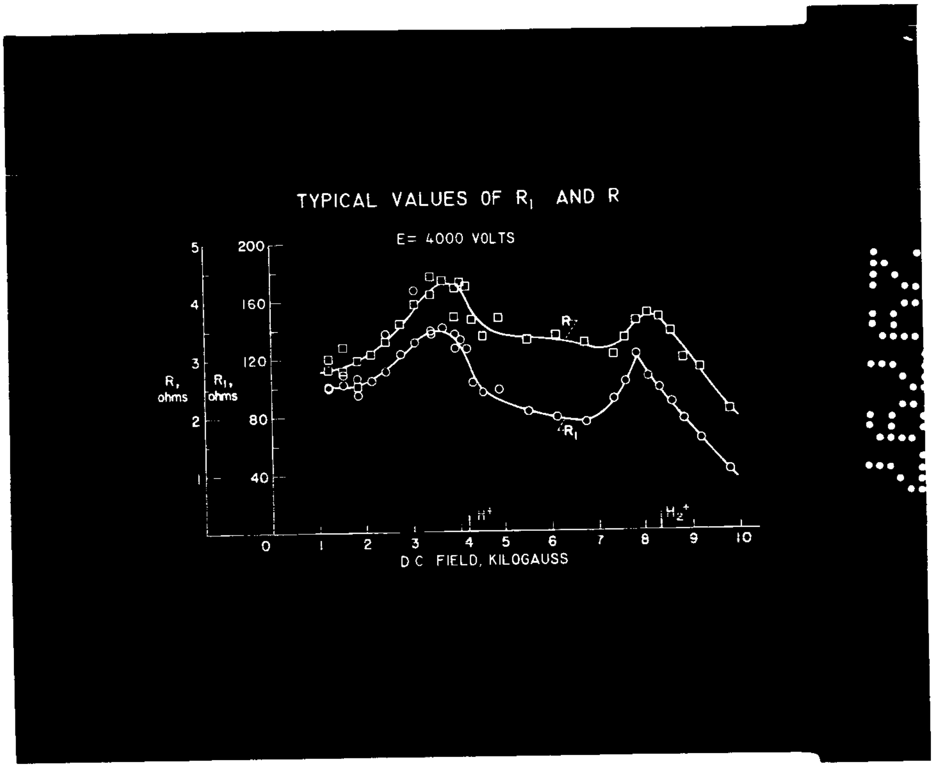


MODEL CIRCUIT AND EQUATIONS
ACTUAL CIRCUIT
EQUIVALENT CIRCUIT

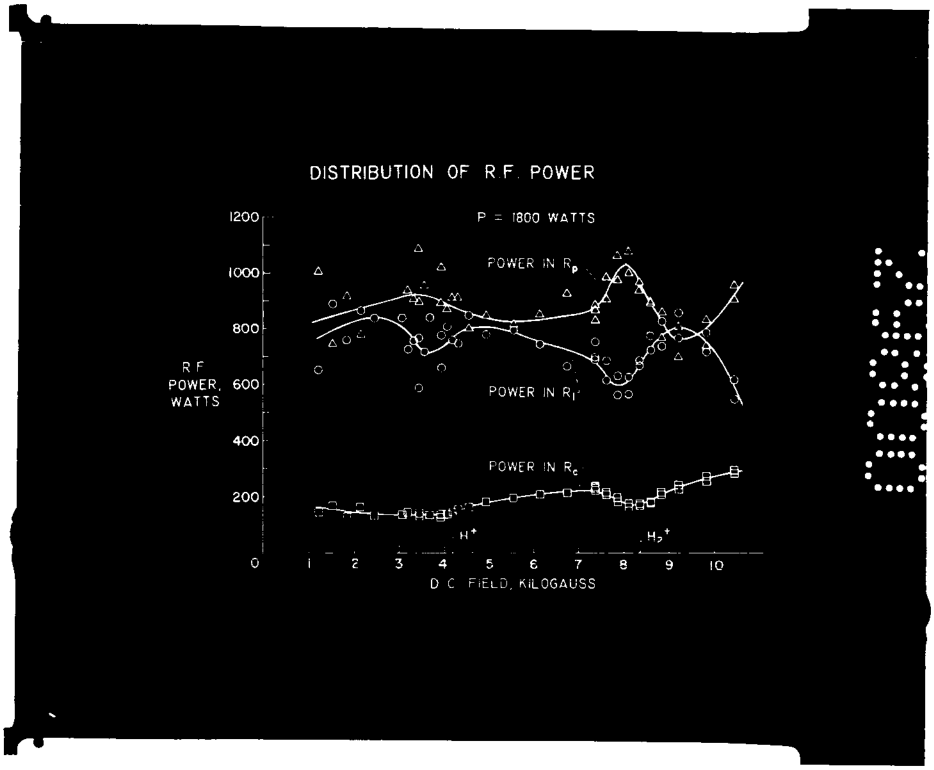
II


TYPICAL EXPERIMENTAL DATA
VOLTAGE AT CONSTANT P = 1800 W
POWER AT CONSTANT E = 4000 V
R F POWER, KILO-WATTS
COIL VOLTAGE, VOLTS PEAK
5000
4000
3000
2000
1000
0
4
3
2
1
1
2
3
4
5
6
7
8
9
10
H^+
H_2^+
D.C. FIELD, KILOGAUSS

III

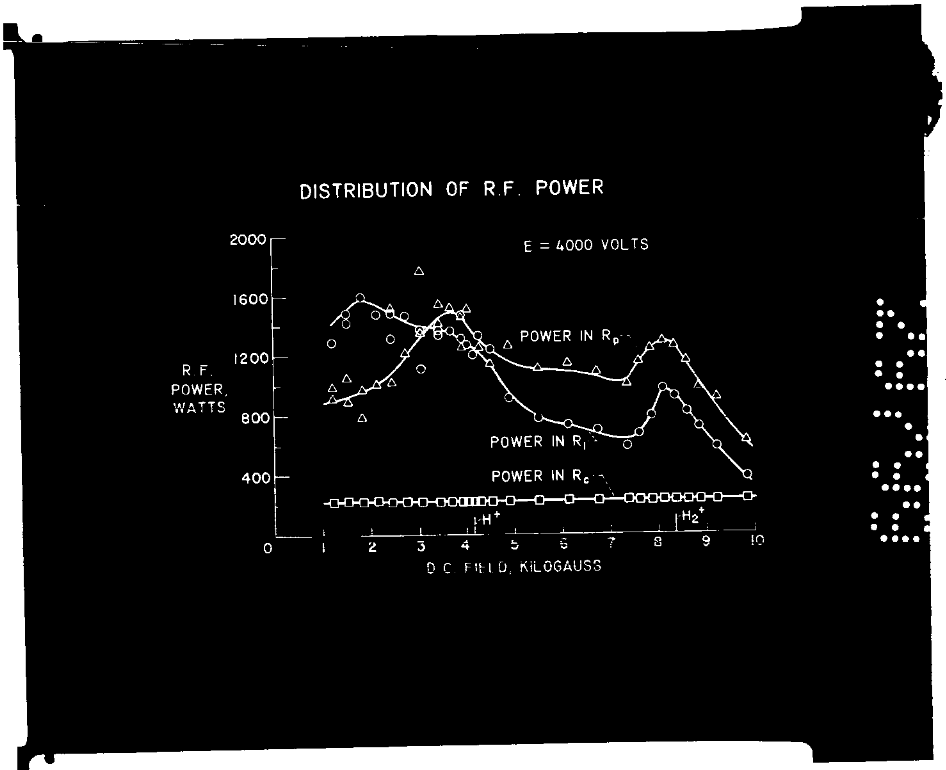

TYPICAL VALUES OF R1 AND R
E= 4000 VOLTS
R, ohms
R1, ohms
R
R1
H+
H2+
DC FIELD, KILOGAUSS

IV

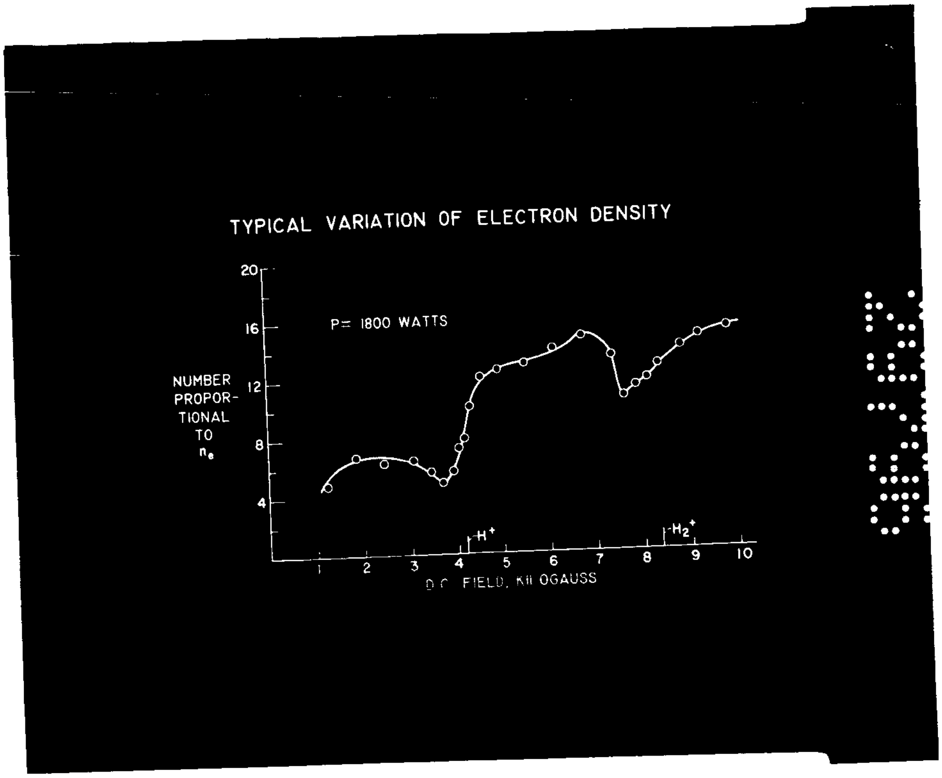


DISTRIBUTION OF R.F. POWER
P = 1800 WATTS
POWER IN R_p
POWER IN R_l
POWER IN R_c
R.F. POWER, WATTS
1200
1000
800
600
400
200
0
H^+
H_2^+
1
2
3
4
5
6
7
8
9
10
D.C. FIELD, KILOGAUSS

V


DISTRIBUTION OF R.F. POWER
E = 4000 VOLTS
R.F. POWER, WATTS
2000
1600
1200
800
400
0
POWER IN R_p
POWER IN R_l
POWER IN R_c
H^+
H_2^+
1 2 3 4 5 6 7 8 9 10
D.C. FIELD, KILOGAUSS

VI



TYPICAL VARIATION OF ELECTRON DENSITY
P= 1800 WATTS
NUMBER PROPORTIONAL TO n_e
20
16
12
8
4
1
2
3
4
5
6
7
8
9
10
H^+
H_2^+
D.C. FIELD, KILOGAUSS

VII